Quarterly Reports on the Meridional Heat Transport Variability in the Atlantic Ocean

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1. Project Summary

Goal/Rationale: To contribute to the assessment of the state of the ocean by providing quarterly reports on the meridional heat transport in the North and South Atlantic oceans. This heat transport is directly related to the role that this basin plays in the meridional overturning circulation (MOC) and is an important benchmark for integrated air-sea fluxes and numerical model performance. Models indicate that the variability on the MOC has important consequences for the global climate. This project directly addresses the goal of the ocean observing system for climate to better understand the extent to which the ocean sequesters heat; to identify where heat enters the ocean and where it emerges to interact with the atmosphere; and to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change.

Project Output: "State of the ocean" quarterly estimates of meridional oceanic heat transport in the center of the subtropical gyres in the North and South Atlantic. This project supports the development of a methodology to estimate heat transport variability using data collected along two High Density Expendable Bathythermograph (XBT) transects operated by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML), satellite data (altimeter and scatterometer), wind products from the National Center for Environmental Prediction (NCEP) reanalysis and products from general circulation models. Quarterly reports are posted on the AOML web site.

General Overview: The Atlantic Ocean is the major ocean basin involved in large-scale northward transports of heat typically associated with the MOC where warm upper layer water flows northwards, and is compensated for by southward flowing North Atlantic Deep Water. This large-scale circulation is responsible for the northward heat flux through the entire Atlantic Ocean. Historical estimates of the net northward heat flux in the vicinity of its maximum, which occurs in the North Atlantic roughly at the latitude of the center of the subtropical gyre, range from 0.9 PW[1] to 1.6 PW, while estimate in the 30°S to 35°S band are even more uncertain,

[1] PW is PetaWatt or 10^{15} Watts, a unit of power commonly used for ocean heat transports.

ranging from negative to more than 1 PW. While much of this variability may be a consequence of the different methods used to estimate the heat transport, natural variability cannot be ruled out. The importance of this heat transport to the world climate together with the possibility of monitoring its variability motivates this project.

Scope: AOML collects XBT data on two transects spanning the subtropical oceans: in the North Atlantic since 1995 (quarterly repeats) along AX7 running between Spain and Miami, Florida, and in the South Atlantic since 2002 (twice per year until 2004 and quarterly thereafter) along AX18 between Cape Town, South Africa, and Buenos Aires, Argentina. These data capture the upper limb of the MOC transport. In the North Atlantic much of the northward transport is confined to a strong boundary current through the Florida Straits, where XBT data is augmented with other data from the NOAA/CPO funded Western Boundary Time Series program. This program funds the analysis of the heat transport across these two sections, culminating in values published within three months of the completion of each XBT realization on the AOML web site (and other journal articles as appropriate).

2. Scientific and Observing System Accomplishments

Products Delivered: Quarterly reports were designed to show the estimated heat transport across the AX07 and AX18 transects (Figure 1 and 2), which are posted quarterly on AOML's state of the ocean web site at http://www.aoml.noaa.gov/phod/soto/mht/index.php. Each figure shows: the position of the most recent XBT transect (red) and the position of the all the transects completed to date (blue) (Top left panel); the temperature section corresponding to the last section (top right panel); the time series of the obtained values for the different components of the heat transport (bottom left) and the annual cycle of the heat transport components (bottom right).

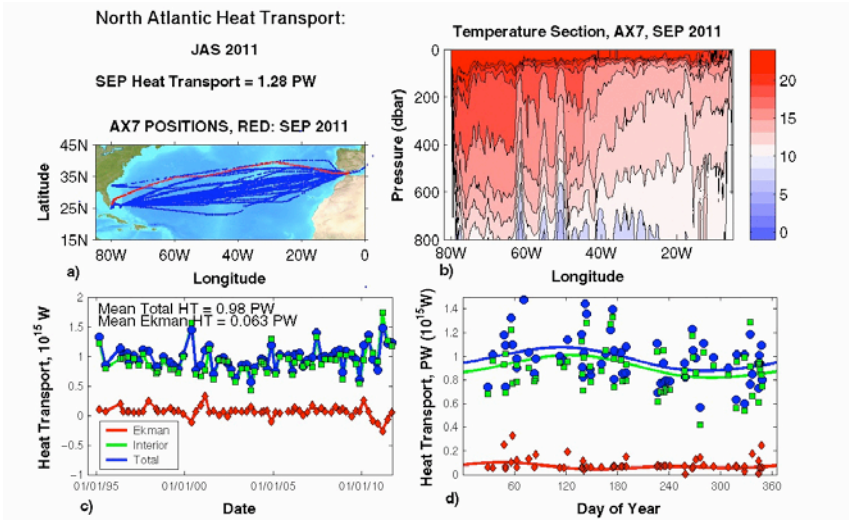

Figure 1: *Report for the July-August-September quarter of 2011 for North Atlantic Meridional Heat transport along the AX7 high density XBT transect. Transport results based on September 2011 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were decomposed into the geostrophic (interior) and Ekman components and their total (lower left).*

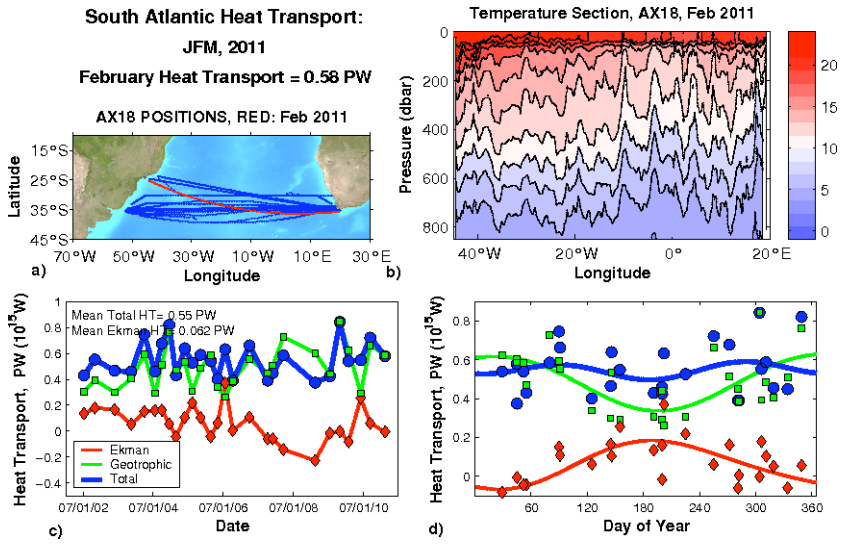

Figure 2: *Report for the January-February-March quarter of 2011 for South Atlantic Meridional Heat transport along the AX18 high density XBT transect. Transport results based on February 2011 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were estimated using a shallow (green squares) and deep (red diamonds) reference level (lower left). Total heat transports demonstrate no significant seasonal signal because the seasonal signal in the Ekman layer is directly out of phase with the geostrophic signal (lower right).*

Values of heat transport are given in PW (1 PW = 10^{15}W). One PW is equivalent to the amount of electricity produced by *one million* of the largest nuclear power plants in existence today (the largest nuclear plants produce about 1 gigawatt of electrical power).

This analysis quantifies the transport of heat in the North and South Atlantic. During the previous year, no abrupt climate change signals were observed, directly addressing the ocean observing systems program requirement to evaluate the heat transports within the oceans and assess abrupt climate change and variability. Papers highlighting the improved understanding of the climate system are described below.

Scientific Findings:

The variability of the Atlantic Meridional Overturning Circulation (AMOC) and its effect on the net northward meridional heat transport (MHT) in the South Atlantic are examined using a trans-basin expendable bathythermograph (XBT) High Density transect at 35°S (AX18). An update to this time series is shown in Figure 3 (Garzoli et al in preparation). The mean MHT is 0.55 ± 0.13 PW and no significant trend is observed from 2002 to 2011. The MOC varies from 14.4 to 22.7 Sv with a mean value of 18.1 ± 2.3 Sv and the maximum overturning transport is found at a depth that is deeper than that in the North Atlantic (mean depth of 1250 m). Statistical analysis suggests that an increase of 1 Sv in the MOC leads to an increase of the MHT of 0.04 ± 0.02 PW. The work by Garzoli et al verifies that a heat transport time series can be reconstructed in spite of changing the ending port on the west side of the Atlantic along the AX18 transect; the paper uses the OFES model and Argo and air-sea flux data from NCEP to examine the heat balance in the latitude range between the two different ports used for AX18 and shows that a small seasonal

correction can be applied to 'normalize' the heat transport from one section to add to the time series of values at the other section.

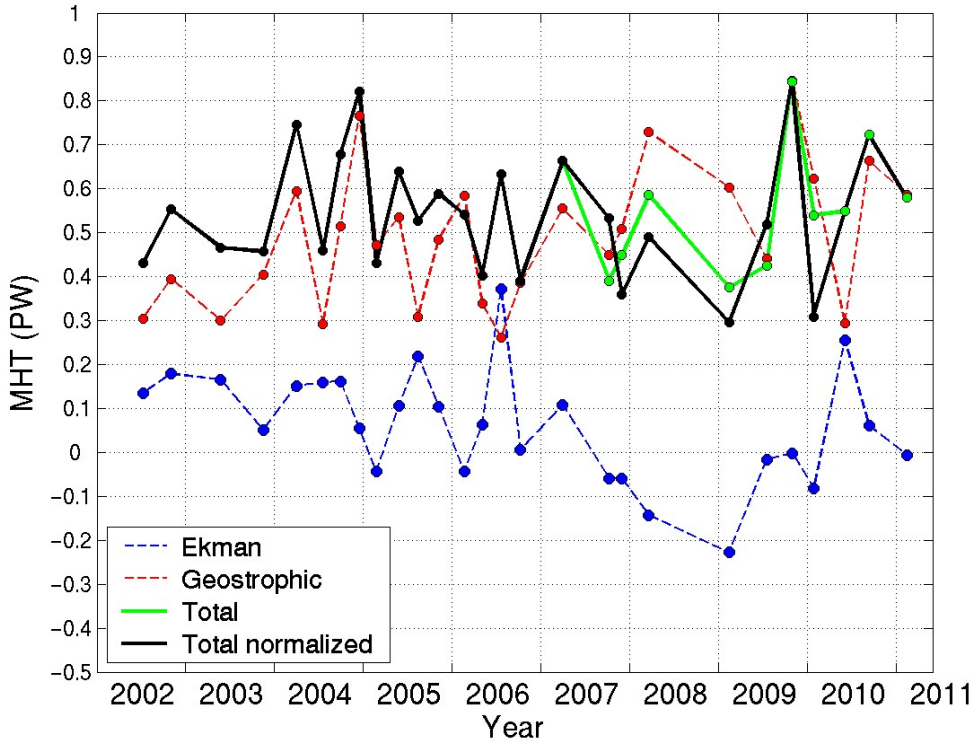

Figure 3: *MHT as a function of time estimated from AX18 transects (solid black line). The geostrophic and Ekman components of the MHT are shown in red and blue, respectively. For data collected after October 2007, in green is shown the values of the MHT normalized to 35°S (Garzoli et al, 2012, in preparation).*

In other published work, the interocean exchanges of heat and meridional mass transport of water from the South Atlantic with the Pacific and Indian Oceans is examined using the output from the ocean general circulation model for the Earth Simulator (OFES) during the period 1980–2006 (Dong et al 2011a), validated by heat transport and meridional overturning transport estimates derived from XBT observations. The meridional heat transport from OFES shows a similar response to AMOC variations to that derived from XBT observations: a 1 Sv (1 Sv $=10^6$ m^3 s^{-1}]) increase in the AMOC strength would cause a 0.054 +/- 0.003 PW increase in MHT at approximately 34°S (Figure 4). The main feature in the AMOC and MHT across 34°S is their increasing trends during the period 1980–93. Separating the transports into boundary currents and ocean interior regions indicates that the increase in transport comes from the ocean interior region, suggesting that it is important to monitor the ocean interior region to capture changes in the AMOC and MHT on decadal to longer time scales. The linear increase in the MHT from 1980 to 1993 is due to the increase in advective heat converged into the South Atlantic from the Pacific and Indian Oceans. Of the total increase in the heat convergence, about two-thirds is contributed by the Indian Ocean through the Agulhas Current system, suggesting that the warm-water route from the Indian Ocean plays a more important role in the northward-flowing water in the upper branch of the AMOC at 34°S during the study period.

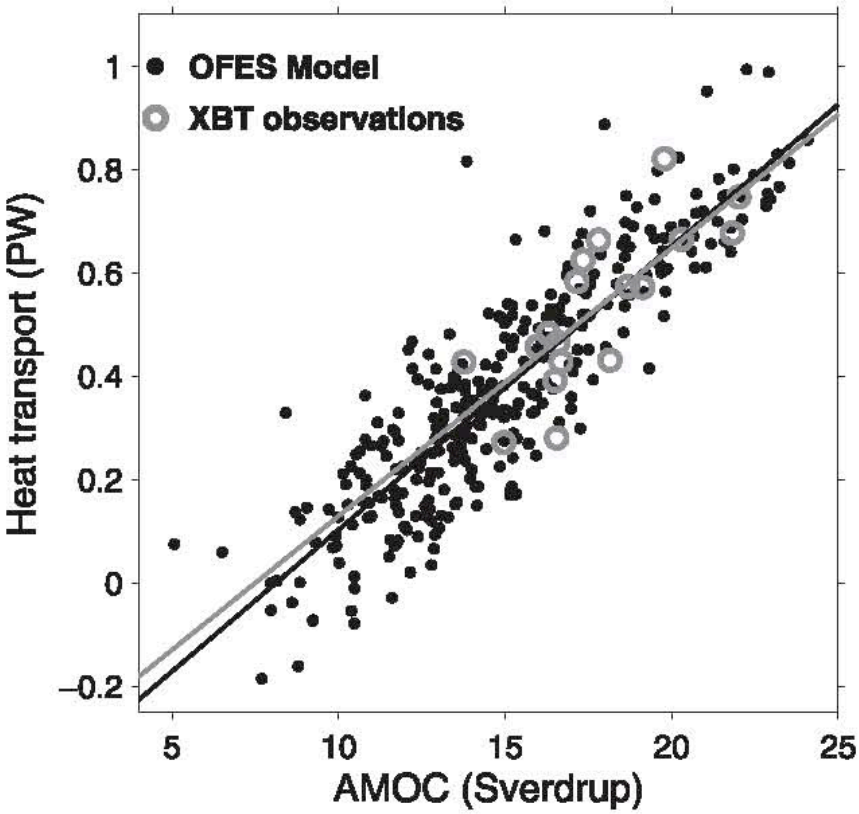

Figure 4: *Scatter plot of the strength of the AMOC vs total MHT across 34S. Dots and circles correspond to OFES and XBT observations, respectively. The black and gray lines indicate the regression of the heat transport to the AMOC from OFES and XBT observations, respectively.*

Dong, et al (2011b) examination of the MOC and MHT from GFDLCM2.1 and GFDLCDA models at 34°S in the South Atlantic shows that both the GFDLCM2.1 and GFDLCDA before assimilating Argo data produce similar time mean values of MOC and MHT to those estimated using XBT measurements. However, the boundary currents are too weak and interior overturning flow is relatively strong. After 2002, when Argo data started being assimilated, the performance of GFDLCDA in simulating the MOC processes was greatly improved, though the mean values of the MOC and MHT are lower compared to the estimates from AX18 transect. The boundary currents were twice as much as those prior to 2003, and the interior overturning flow is reduced by 20% due to a better representation of salinity field (Figure 5). The improvement of the boundary currents, despite the lack of Argo data at the boundaries, in particular the western boundary, is probably due to better temperature/salinity representation at the interior side of the boundaries. The weak MOC and MHT since 2003 in GFDLCDA is likely due to the slightly stronger southward transport in the western boundary and slightly weaker northward transport in the eastern boundary in GFDLCDA than those estimated from XBT measurements. Those comparisons suggest the importance of the Argo float measurements in improving data-assimilating model performance in representing the MOC processes. The lack of Argo data at the boundaries may be responsible for the weak MOC, suggesting that measurements from other platforms are needed at the boundaries to further improve MOC processes in data-assimilating models.

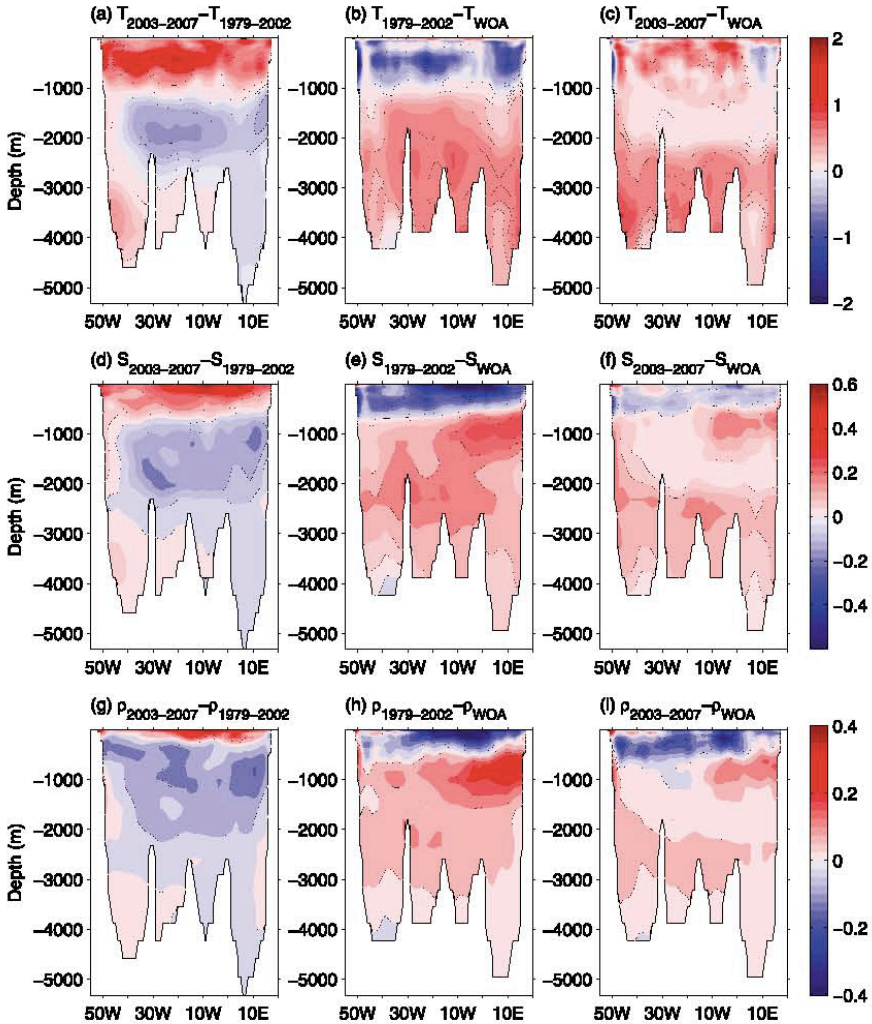

Figure 5: *Temperature differences between (a) GFDLCDA 2003–2007 and GFDLCDA 1979–2002, (b) GFDLCDA 1979–2002 and WOA09, and (c) GFDLCDA 2003–2007 and WOA09. (d, e, and f) Similar to Figures 5a, 5b, and 5c, respectively, but for salinity differences. (g, h, and i). The corresponding density differences. Units are degree Celsius for temperature differences, psu for salinity differences, and kg m−3 for density differences.*

In other related work in the North Atlantic several papers were published including an update of the meridional overturning circulation (MOC) array along 26N from the Rapid/MOC/MOCHA/WBTS program (Baringer et al., 2011; Rayner et al., 2011), an extension of the MOC time series near 26N using historical data (Longworth et al., 2011) and a paper tracing Labrador Sea Water pathways (van Sebille et al., 2012). Numerical models were also used to show that interocean exchanges in the South Atlantic are needed to explain the model-observed multidecadal variability of the MOC and heat transport in the Atlantic; local air-sea forcing is insufficient to explain the variability (Lee et al., 2011). Figure 6 from Lee et al (2011) shows the net heat content in the Atlantic and the MHT along 35S simulated in three models: one forced by the globally variable surface heat fluxes (EXP_CTR), one forced with variable heat fluxes only in the North Atlantic north of 30°S (EXP_ATL) and one model forced with variable heat fluxes outside the region of the North Atlantic (EXP_REM). These model results fully support the hypothesis that the enhanced warming of the Atlantic Ocean during the later

half of the 20th century is largely due to the increased ocean heat transport into the Atlantic basin across 30°S.

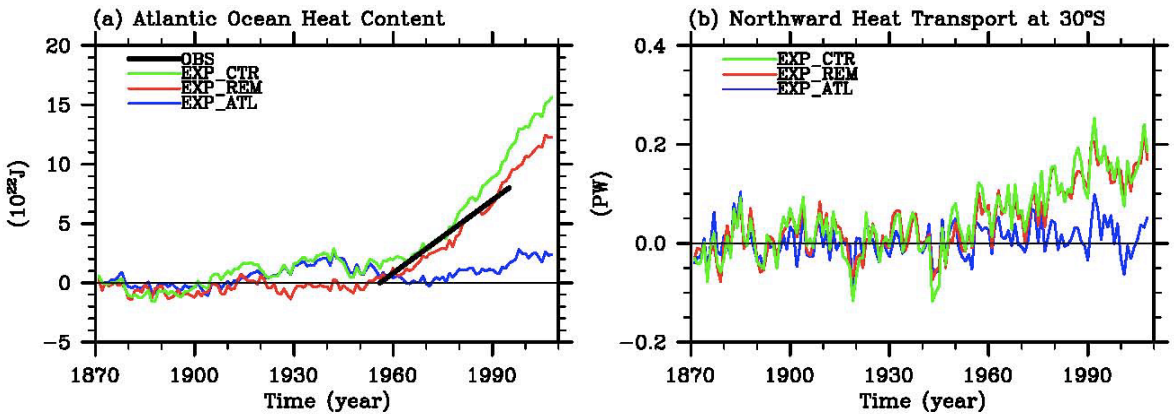

***Figure 6**: (a) Simulated Atlantic Ocean heat content change in the upper 3000m and (b) simulated northward ocean heat transport in the South Atlantic at 30oS in reference to 1871-1900 obtained from the three model experiments. The thick black line in (a) is the observed trend of the Atlantic Ocean heat content increase*

In future work, we will assess the potential of sea height anomaly observations derived from satellite altimetry to compute geostrophic meridional heat transport in the South Atlantic. As an initial step, historical relationships between sea height and depth of isotherms are used to derive synthetic temperature profiles (Figure 7), which are then used, following the same procedures as XBT temperature profiles to compute the heat transport. Preliminary results (Figure 7) indicate the main features obtained from XBT observations are also reproduced in the altimetric estimates. Once this methodology is refined, similar zonal estimates will be carried out at different latitudes since 1993, taking advantage of the long time series provided by satellite altimetry.

Risks:

Heat transport analysis requires the underlying data to sustain time series information. During FY2011, the high-density transect AX18 was occupied twice during the year due to shipping route changes. Recruitment efforts have resulted in finding new ships that will provide the necessary coverage.

Web site:

The analysis project funded here can be accessed here:
http://www.aoml.noaa.gov/phod/soto/mht/index.php

The high-density XBT data that are relied upon for this analysis can be found here:
http://www.aoml.noaa.gov/phod/hdenxbt/index.php#

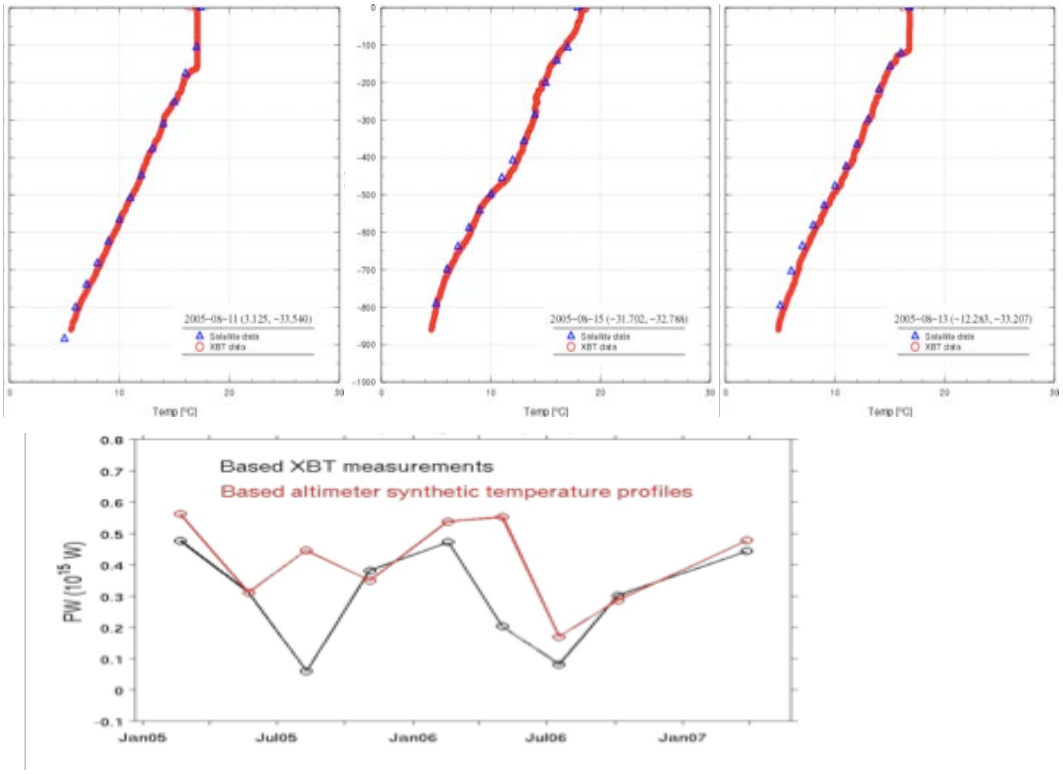

Figure 7*: Top: Three examples of estimated temperature profiles derived from altimetric observations. Bottom: Preliminary examples of the heat transports from altimetry profiles as compared to XBT profiles.*

2.1. Outreach and Education

M. Baringer is a contributing author for Chapter 3: Observations: Oceans for Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Intergovernmental Panel on Climate Change Fifth Assessment Report. She co-authored a recently accepted paper with postdoctoral fellow Eric van Sebille looking at the propagation pathways of Labrador Sea Water in the North Atlantic (the postdoctoral fellow was support under the MOCHA/Rapid/WBTS program).

3. Publications and Reports

3.1. Publications by Principal Investigators

Referred Publications (electronic versions of published articles are available via hyperlink): FY2012

Meinen, C. S., William E. Johns, Silvia L. Garzoli, Erik van Sebille, Darren Rayner, Torsten Kanzow, and Molly O. Baringer, 2011. Variability of the Deep Western Boundary Current at 26.5°N during 2004-2009. *Deep-Sea Res., accepted.*

van Sebille, Erik, Molly O. Baringer, William E. Johns, Christopher S. Meinen, Lisa M. Beal, M. Femke de Jong, and Hendrik M. van Aken, 2011. Propagation pathways of classical

Labrador Sea Water from its source region to 26o N, Journal of Geophysical Research Oceans, 116, C12027, doi:10.1029/2011JC007171.

FY2011

Baringer, M. O., T. O. Kanzow, C. S. Meinen, S. A. Cunningham, D. Rayner, W. E. Johns, H. L. Bryden, Eleanor Faika-Williams, J. J-M. Hirschi, M. P. Chidichimo,L. M. Beal and J. Marotzke, 2011. Meridional Overturning Circulation Observations in the Subtropical North Atlantic, in State of the Climate in 2010, Blunden, J., D. S. Arndt, M. O. Baringer (eds.), *Bull. Am. Met. Soc*., 92, S95–S98. doi: 10.1175/1520-0477-92.6.S1

Blunden, J., D. S. Arndt, M. O. Baringer, 2011: State of the Climate in 2010. Bull. Amer. Meteor. Soc., 92, S1–S236. doi: 10.1175/1520-0477-92.6.S1

Di Nezio, P.N., and G. Goni, 2011: Direct Evidence of Changes in the XBT Fall-rate Bias During 1986-2008. *Journal of Atmospheric and Oceanic Technology*, 28(11), 1569-1578,doi:10.1175/JTECH-D-11-00017.1.

Dong, S., M. Baringer, G. Goni and S. Garzoli, 2011. Importance of the assimilation of Argo Float Measurements on the Meridional Overturning Circulation in the South Atlantic. Geophysical Research Letters, 38, L18603, doi:10.1029/2011GL048982.

Dong, S. S. Garzoli and M. Baringer, 2011. The Role of inter-ocean exchanges on decadal variations of the northward heat transport in the South Atlantic, J. Phys. Oceano., 41(8):1498-1511.

Garzoli, S.L and R. Matano, 2011: The South Atlantic and the Atlantic Meridional Overturning Circulation. Deep-Sea Research II, 58(17-18):1837-1847, doi:10.1016/j.dsr2.2010.10.063.

Goni, G.J., F. Bringas, and P.N. Di Nezio, 2011: Observed Low Frequency Variability of the Brazil Current Front. *Journal of Geophysical Research*, 116, C10037, doi:10.1029/2011JC007198.

Goni, G.J., J.A. Knaff, and I.-I. Lin, 2011: Tropical Cyclone Heat Potential. In "State of the Climate in 2010", J. Blunden, D. S. Arndt, M. O. Baringer (eds.). *Bulletin of the American Meteorological Society*, 92(6):S132-S134.

Johns, W. E., M. O. Baringer, L. M. Beal, S. A. Cunningham, T. Kanzow, H. L. Bryden, J. Hirschi, J. Marotzke, C. Meinen, B. Shaw, and R. Curry, 2010. Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5 ºN. *J. Clim*., 24(10):2429-2449.

Kanzow. T., S.A. Cunningham, W.E. Johns, J. J-M. Hirschi, J. Marotzke, M. O. Baringer, C.S. Meinen, M. P. Chidichimo, C. Atkinson, L. M. Beal, H. L. Bryden, J. Collins, 2010. Seasonal variability of the Atlantic meridional overturning circulation at 26.5^{o}N. *Journal of Climate*, *23*, doi: 10.1175/2010JCLI3389.1171.

Lee S.-K., W. Park, E. van Sebille, M. O. Baringer, C. Wang, D. B. Enfield, S. Yeager, and B. P. Kirtman, 2011. What Caused the Significant Increase in Atlantic Ocean Heat Content Since the mid-20th Century? Geophysical Research Letters, doi:10.1029/2011GL048856.

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Lumpkin R., G. Goni and K. Dohan, 2011: State of the Ocean in 2010: Surface Currents. In "State of the Climate in 2010", *Bulletin of the American Meteorological Society*, 92(6):S92-S95.

Nagamani, P.V., M.M. Ali, G.J. Goni, P. Di Nezio, J.C. Pezzullo, T.V.S. Udaya Bhaskar, V.V. Gopalakrishna, and N. Kurian, 2011: Validation of Satellite-Derived Tropical Cyclone Heat Potential With In situ Observations in the North Indian Ocean. *International Journal of Remote Sensing*, in press.

Perez, R.C., S.L. Garzoli, C.S. Meinen, and R.P. Matano, 2011: Geostrophic Velocity Measurement Techniques for the Meridional Overturning Circulation and Meridional Heat Transport in the South Atlantic. *Journal of Atmospheric and Oceanic Techology*, 28:1504-1521.

Rayner, D., Joel J.-M. Hirschi, Torsten Kanzow, William E. Johns, Stuart A. Cuningham, Paul G. Wright, Eleanor Frajka-Williams, Harry L. Bryden, Christopher S. Meinen, Molly O. Baringer, Jochem Marotzke and Lisa M. Beal, 2010.Monitoring the Atlantic Meridional Overturning Circulation, *Deep-Sea Res., Part II*, Topical Studies in Oceanography, Volume 58;1744-1753, ISSN 0967-0645, DOI: 10.1016/j.dsr2.2010.10.056.

Conference Presentations:

Meinen, C. S., W. E. Johns, S. L. Garzoli, S. A. Cunningham and T. Kanzow, Variability of the Deep Western Boundary Current at 26.5°N, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

C. Atkinson, M. Baringer, L. Beal, H. Bryden, M-P. Chidichimo, J. Collins, S. Cunningham, J. Hirschi, W. Johns, H. Johnson, T. Kanzow, J. Marotzke, D. Marshall, C. Meinen, A. Mujahid, D. Rayner, Z. Szuts, E. Frajka-Williams, Meridional overturning circulation and heat flux array at 26.5°N: Variability observed at periods of minutes to years during the period from April 2004 to April 2009, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

Garzoli, S. L., and C. S. Meinen, Deep Western Boundary Current variability and signal attribution in the North Atlantic, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

van Sebille, E., W. Johns, M. Baringer, C. Meinen, L. Beal, M. F. de Jong, H. van Aken, Propagation pathways of classical Labrador Sea Water from its source region to 26°N, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)